AASHTO Strength Design Checks

www.mbrace3d.com

Purpose

1. Understand the different AASHTO strength design checks (10th Edition, 2024).

2. Describe how mBrace3D (v4.0) performs these checks automatically.

3. Illustrate these new capabilities on AISC/NSBA Design Example 4, a typical curved, continuous, plate girder bridge.

Method Outline

mBrace3D v4.0 enables the <u>automation</u> of a variety of AASHTO LRFD strength design checks, by:

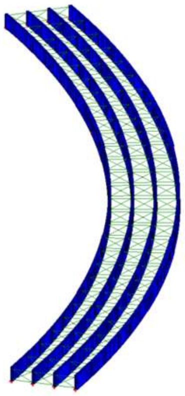
1. <u>Extracting moment and shear results</u> from all the required load cases:

<u>DC1-S</u>	Effects due to the self-weight of the steel superstructure only
<u>DC1-C</u>	Effects due to the wet concrete load (before composite action develops)
<u>DC2</u>	Effects due to superimposed dead loads (parapets, barriers)
<u>DW</u>	Effects due to the wearing surface load
<u>LL+IM</u>	Live load effects, including dynamic allowance

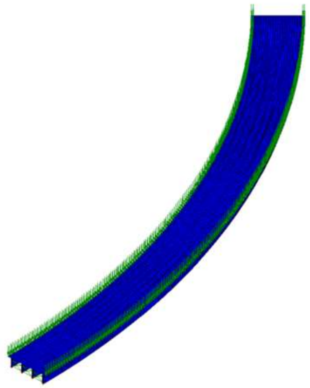
2. <u>Computing the corresponding principal bending (f_b) and lateral bending (f_l) stresses</u>, using the appropriate section modulii (non-composite section, short-term and long-term composite sections)

3. <u>Evaluating the strength design checks</u> from the AASHTO LRFD Bridge Design Specifications (10th Edition)

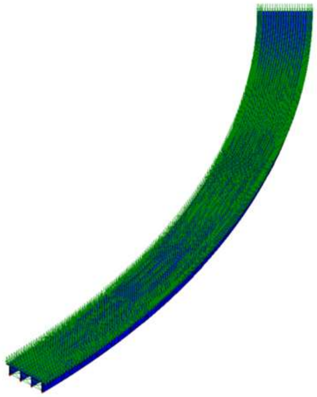
Step 1 – Load Cases



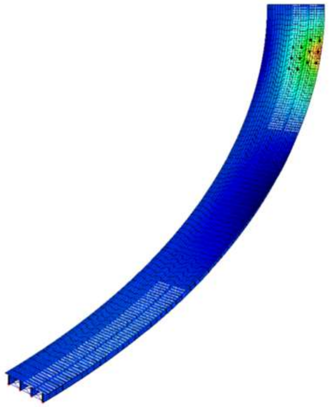
Steel superstructure only
DC1-S, DC1-C



Long-term composite section
DC2



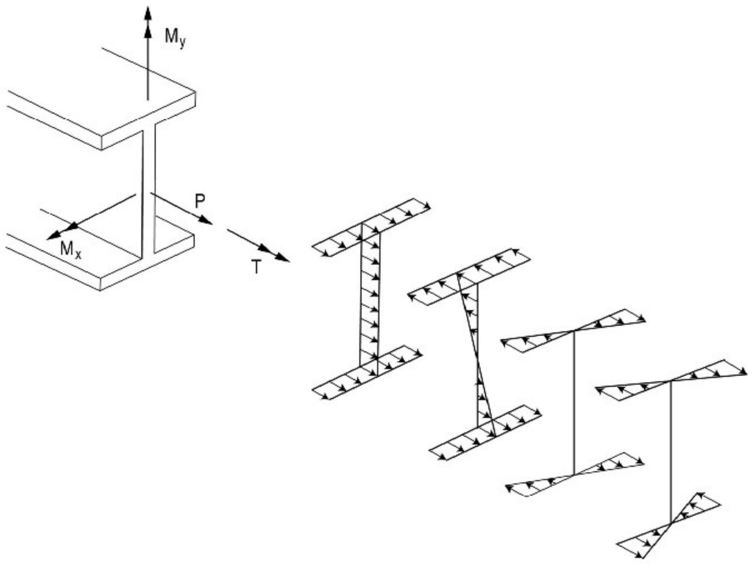
Long-term composite section
DW



Short-term composite section
LL+IM

For LL+IM, the envelope moment and shear values are derived using an <u>influence surface analysis</u>.

Step 2 – Principal and Lateral Bending Stresses



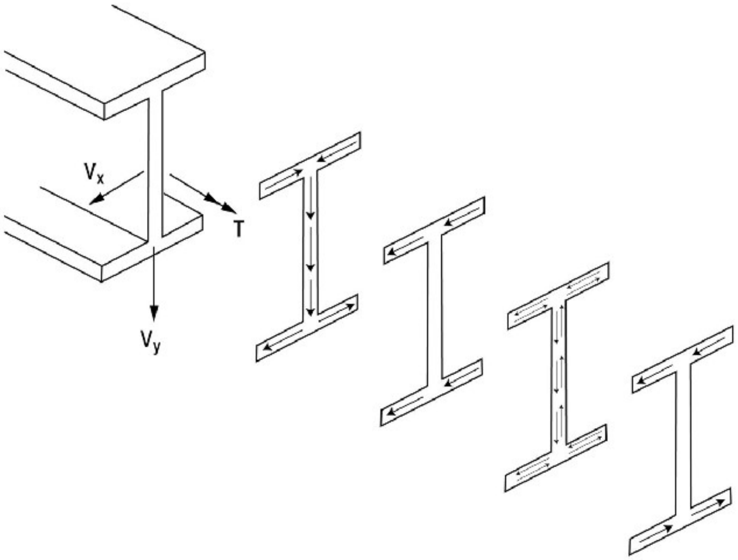
$$\text{Total Normal Stress} = \sigma = \frac{P}{A} + \frac{M_x\, y}{I_x} + \frac{M_y\, x}{I_y} + \text{Warping Normal Stress}$$

The <u>bending moment</u> (M) is obtained by computing the position of the elastic neutral axis, and integrating longitudinal stresses with respect to that axis.

<u>Principal bending stresses</u> (f_b) are obtained by dividing the resulting bending moment by the appropriate section modulus.

<u>Lateral bending stresses</u> (f_l) are obtained by subtracting the longitudinal stress at the flange center node from the stress at the flange tip.

Step 2 – Resultant Shear Force



$$\text{Total Shear Stress} = \tau = \frac{V_y Q_x}{I_x t} + \frac{V_x Q_y}{I_y t} + \text{St. Venant Torsion} + \text{Warping Torsion}$$

The resultant <u>shear force</u> (V) is obtained by integrating the vertical shear stresses over the section.

Step 3 – Strength Design Checks – Positive Bending

Chapter 6.10.6.2.2 – Composite Sections in Positive Flexure:

> "Composite sections in [] horizontally curved steel-girder bridges shall be considered as noncompact sections and shall satisfy the requirements of Article 6.10.7.2."

Chapter 6.10.7.2 – Noncompact Sections:

For the top flange (compression flange), verify Eq. 6.10.7.2.1-1: $f_{bu} \leq \phi_f F_{nc}$

For the bottom flange (tension flange), verify Eq. 6.10.7.2.1-2: $f_{bu} + \frac{1}{3} f_l \leq \phi_f F_{nt}$

Also, Chapter 6.10.1.6 – Flange Stresses and Member Bending Moments:

For the bottom flange (discretely braced), verify Eq. 6.10.1.6-1: $f_l \leq 0.6 F_{yf}$

Step 3 – Strength Design Checks – Negative Bending

Chapter 6.10.6.2.3 – Composite Sections in Negative Flexure and Noncomposite Sections:

> "Sections in [] horizontally curved steel-girder bridges shall be considered as proportioned according to the provisions specified in Article 6.10.8."

Chapter 6.10.8 – Flexural Resistance – Composite Sections in Negative Flexure and Noncomposite Sections:

For the bottom flange (discretely braced flange in compression), verify Eq. 6.10.8.1-1: $f_{bu} + \frac{1}{3} f_l \leq \phi_f F_{nc}$

Noting that this check has to be conducted for 2 limit states:

Flange local buckling (FLB)
Lateral-torsional buckling (LTB)

For the top flange (continuously braced flange in tension), verify Eq. 6.10.8.1.3-1: $f_{bu} \leq \phi_f R_h F_{yf}$

Step 3 – Strength Design Checks – Bending

Notes:

1. For bending checks, the hybrid factor (R_h) is calculated automatically, following Chapter 6.10.1.10.1.
2. The web load-shedding factor (R_b) is calculated automatically, following Chapter 6.10.1.10.2.
3. For lateral-torsional buckling (LTB) checks, the unbraced length (L_b) is also calculated automatically, based on the cross-frame arrangement implemented in the mBrace3D model (X-frames and K-frames).
   A moment gradient factor (C_b) of 1.0 is conservatively assumed.
4. Lateral bending stresses (f_l) for the LL+IM load case are obtained from the finite element analysis (FEA) model directly, setting them as the response quantity for the influence analysis. This is a conservative approach, as the corresponding critical live load pattern may not be coincident with the one obtained for the composite bending moment.

Step 3 – Strength Design Checks – Shear

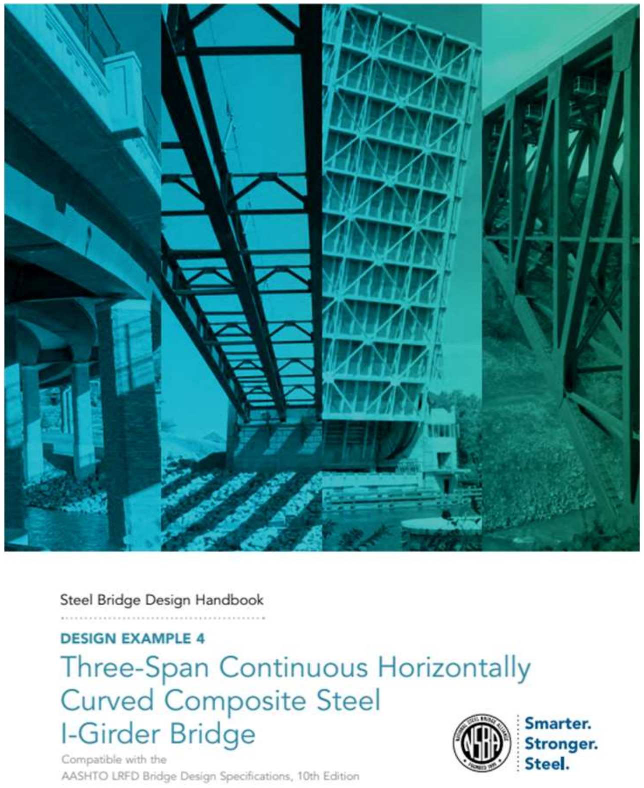
Chapter 6.10.9.1 – Shear Resistance:

For the calculation of shear resistance, the transverse web stiffener spacing at the design location is determined using the connecting plates (for the X-frames and K-frames) included in the finite element model, together with additional user-defined transverse web stiffeners not explicitly represented in the mesh.
These supplementary stiffeners are used to limit the stiffener spacing at the design location, resulting in a more accurate assessment of panel shear resistance.

The nature of the panel ("end panel" or "interior panel") is also automatically determined by the software.

Verify Eq. 6.10.9.1-1: $V_u \leq \phi_v V_n$

AISC/NSBA Design Example 4 – Design Locations



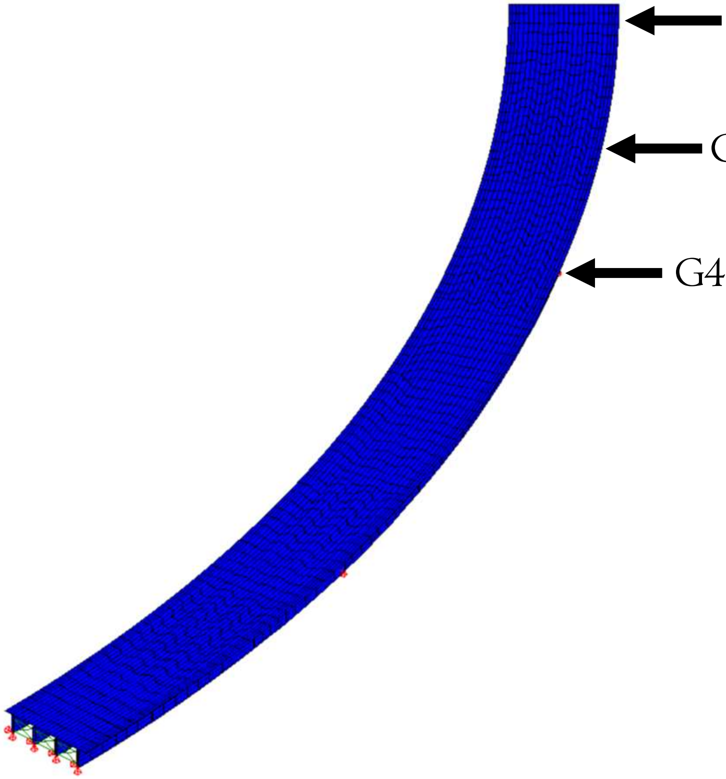
Steel Bridge Design Handbook

DESIGN EXAMPLE 4

Three-Span Continuous Horizontally Curved Composite Steel I-Girder Bridge

Compatible with the
AASHTO LRFD Bridge Design Specifications, 10th Edition

Smarter.
Stronger.
Steel.



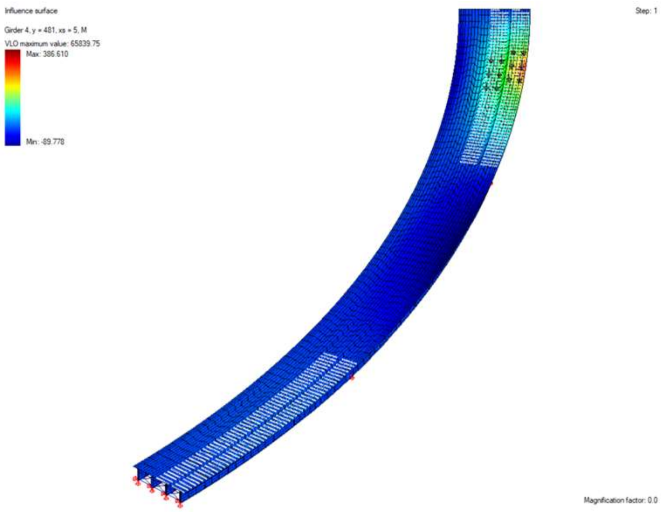
G4-3: Shear, Abutment 2

G4-1: Positive bending, Span 3

G4-2: Negative bending, Pier 2

Source: https://www.aisc.org/bridges/bridge-resource-center/sbdh-example-4-three-span-continuous-horizontally-curved-composite-steel-i-girder-bridge/

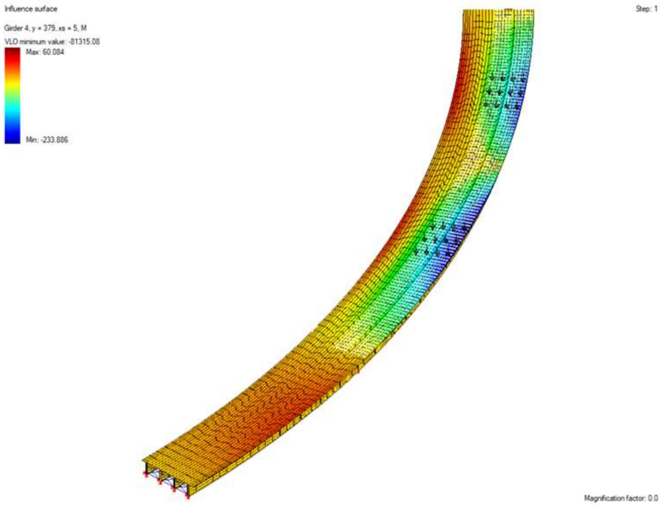
AISC/NSBA Design Example 4 – Influence Surfaces



G4-1: Positive bending, Span 3

M_{max} = 5,487 kip · ft

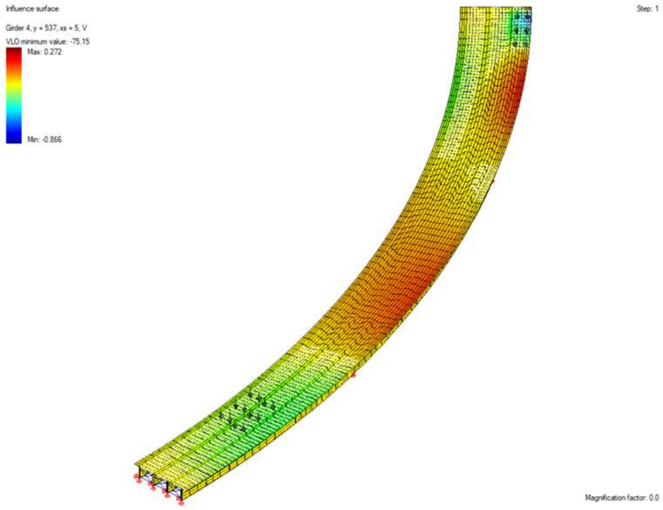
(Published value: 5,125 kip · ft)



G4-2: Negative bending, Pier 2

M_{min} = -6,776 kip · ft

(Published value: -6,726 kip · ft)



G4-3: Shear, Abutment 2

V_{min} = -75.1 kips

AISC/NSBA Design Example 4 – Positive Bending

I. Positive bending checks

I.1 Compute composite section properties

Composite section properties (positive bending)

Long-term (3n) section properties with transformed deck

Modular ratio	n	7.56	
Equivalent reduced width (3n)	$b_{eff,3n}$	4.89	in
Equivalent reduced area (3n)	$A_{c,3n}$	44.02	in^2
Location of the neutral axis	NA_{3n}	42.91	in
Moment of inertia	IA_{3n}	213175	in^4
Distance from neutral axis to top of steel	$y_{tf,3n}$	30.91	in
Distance from neutral axis to bottom of steel	$y_{bf,3n}$	55.59	in
Distance from neutral axis to top of web	$D_{tf,3n}$	29.91	in
Distance from neutral axis to bottom of web	$D_{bf,3n}$	28.41	in
Top section modulus	$S_{tf,3n}$	6897	in^3
Bottom section modulus	$S_{bf,3n}$	3835	in^3

Short-term (n) section properties with transformed deck

Modular ratio	n	7.56	
Equivalent reduced width (n)	$b_{eff,n}$	14.67	in
Equivalent reduced area (n)	$A_{c,n}$	132.07	in^2
Location of the neutral axis	NA_n	28.26	in
Moment of inertia	IA_n	294105	in^4
Distance from neutral axis to top of steel	$y_{tf,n}$	16.26	in
Distance from neutral axis to bottom of steel	$y_{bf,n}$	70.24	in
Distance from neutral axis to top of web	$D_{tf,n}$	15.26	in
Distance from neutral axis to bottom of web	$D_{bf,n}$	13.76	in
Top section modulus	$S_{tf,n}$	18092	in^3
Bottom section modulus	$S_{bf,n}$	4187	in^3

Note: Section properties slightly reduced from the published example, for demonstration purposes only.

AISC/NSBA Design Example 4 – Positive Bending

I. Positive bending checks

I.1 Compute composite section properties

I.2 Extract bending moments and lateral bending stresses from the FEA model

Load Factors	
$\gamma_{DC1\text{-}S}$	1.25
$\gamma_{DC1\text{-}C}$	1.25
γ_{DC2}	1.25
γ_{DW}	1.5
γ_{LL+IM}	1.75

Moments		
$M_{DC1\text{-}S}$	669.3	kip*ft
$M_{DC1\text{-}C}$	2656.9	kip*ft
M_{DC2}	547.2	kip*ft
M_{DW}	653.8	kip*ft
M_{LL+IM}	5486.6	kip*ft

	Top flange		Bottom flange	
$fl_{DC1\text{-}S}$	-0.96	ksi	0.46	ksi
$fl_{DC1\text{-}C}$	-4.00	ksi	1.87	ksi
fl_{DC2}	0.77	ksi	0.47	ksi
fl_{DW}	-0.09	ksi	0.58	ksi
fl_{LL+IM}	-0.44	ksi	3.26	ksi

<u>Note:</u> Section properties slightly reduced from the published example, for demonstration purposes only.

AISC/NSBA Design Example 4 – Positive Bending

I. Positive bending checks
   - I.1 Compute composite section properties
   - I.2 Extract bending moments and lateral bending stresses from the FEA model
   - I.3 Compute principal bending stresses

Stresses

Top flange	f_{bu}	DC1-S	-3.24	-4.05	ksi	Bottom flange	f_{bu}	DC1-S	2.60	3.25	ksi
		DC1-C	-12.87	-16.09	ksi			DC1-C	10.31	12.89	ksi
		DC2	-0.95	-1.19	ksi			DC2	1.71	2.14	ksi
		DW	-1.14	-1.71	ksi			DW	2.05	3.07	ksi
		LL+IM	-3.64	-6.37	ksi			LL+IM	15.73	27.52	ksi
		Σ	-21.84	-29.40	ksi			Σ	32.39	48.86	ksi
	f_l	DC1-S	-0.96	-1.20	ksi		f_l	DC1-S	0.46	0.57	ksi
		DC1-C	-4.00	-5.00	ksi			DC1-C	1.87	2.34	ksi
		DC2	0.77	0.96	ksi			DC2	0.47	0.59	ksi
		DW	-0.09	-0.13	ksi			DW	0.58	0.87	ksi
		LL+IM	-0.44	-0.77	ksi			LL+IM	3.26	5.71	ksi
		Σ	-4.71	6.13	ksi			Σ	6.65	10.09	ksi

Note: Section properties slightly reduced from the published example, for demonstration purposes only.

AISC/NSBA Design Example 4 – Positive Bending

I. Positive bending checks

- I.1 Compute composite section properties
- I.2 Extract bending moments and lateral bending stresses from the FEA model
- I.3 Compute principal bending stresses
- I.4 Verify the strength design equations

Strength check, compression flange (Eq. 6.10.7.2.1-1)

	f_{bu}	-29.40	ksi
	F_{nc}	50	ksi
Art. 6.5.4.2	ϕ_f	1.0	
	$\phi_f F_{nc}$	50	ksi
Eq. 6.10.7.2.1-1	$f_{bu} \le \phi_f F_{nc}$	0.59	OK

Strength check, tension flange (Eq. 6.10.7.2.1-2)

	f_{bu}	48.86	ksi
	f_l	10.09	ksi
	$f_{bu}+1/3f_l$	52.22	ksi
	ϕ_f	1.0	
	F_{nt}	50	ksi
	$\phi_f F_{nt}$	50	ksi
Eq. 6.10.7.2.1-2	$f_{bu}+1/3f_l \le \phi_f F_{nt}$	1.04	NG

Strength check, lateral bending (Eq. 6.10.1.6-1)

	f_l	10.09	ksi
	F_{yf}	50	ksi
	$0.6F_{yf}$	30	ksi
Eq. 6.10.1.6-1	$f_l \le 0.6F_{yf}$	0.34	OK

<u>Note:</u> Section properties slightly reduced from the published example, for demonstration purposes only.

AISC/NSBA Design Example 4 – Negative Bending

2. Negative bending checks

2.1 Compute composite section properties

Composite section properties (negative bending)

Long-term (3n) section properties with longitudinal steel reinforcement			
Location of the neutral axis	NA_{3n}	57.01	in
Moment of inertia	IA_{3n}	318511	in^4
Top section modulus	$S_{tf,3n}$	6848	in^3
Bottom section modulus	$S_{bf,3n}$	7409	in^3

Short-term (n) section properties with longitudinal steel reinforcement			
Location of the neutral axis	NA_n	56.18	in
Moment of inertia	IA_n	327375	in^4
Top section modulus	$S_{tf,n}$	7167	in^3
Bottom section modulus	$S_{bf,n}$	7471	in^3

AISC/NSBA Design Example 4 – Negative Bending

2. Negative bending checks
    - 2.1 Compute composite section properties
    - 2.2 Extract bending moments and lateral bending stresses from the FEA model

Load Factors

γ_{DC1-S}	1.25
γ_{DC1-C}	1.25
γ_{DC2}	1.25
γ_{DW}	1.5
γ_{LL+IM}	1.75

Moments

M_{DC1-S}	-1960.5	kip*ft
M_{DC1-C}	-6451.5	kip*ft
M_{DC2}	-1447.1	kip*ft
M_{DW}	-1450.6	kip*ft
M_{LL+IM}	-6776.3	kip*ft

Lateral bending stresses

	Top flange		**Bottom flange**	
fl_{DC1-S}	0.32	ksi	-0.45	ksi
fl_{DC1-C}	1.55	ksi	-1.44	ksi
fl_{DC2}	0.48	ksi	-0.19	ksi
fl_{DW}	0.12	ksi	-0.27	ksi
fl_{LL+IM}	0.67	ksi	-1.18	ksi

AISC/NSBA Design Example 4 – Negative Bending

2. Negative bending checks

   2.1 Compute composite section properties

   2.2 Extract bending moments and lateral bending stresses from the FEA model

   2.3 Compute principal bending stresses

Stresses

Top flange	f_{bu}	DC1-S	3.52	4.40	ksi	Bottom flange	f_{bu}	DC1-S	-3.19	-3.99	ksi
		DC1-C	11.57	14.47	ksi			DC1-C	-10.50	-13.12	ksi
		DC2	2.54	3.17	ksi			DC2	-2.34	-2.93	ksi
		DW	2.54	3.81	ksi			DW	-2.35	-3.52	ksi
		LL+IM	11.35	19.86	ksi			LL+IM	-10.88	-19.05	ksi
		Σ	31.52	45.70	ksi			Σ	-29.26	42.61	ksi
	f_l	DC1-S	0.32	0.40	ksi		f_l	DC1-S	-0.45	-0.57	ksi
		DC1-C	1.55	1.94	ksi			DC1-C	-1.44	-1.80	ksi
		DC2	0.48	0.60	ksi			DC2	-0.19	-0.23	ksi
		DW	0.12	0.18	ksi			DW	-0.27	-0.41	ksi
		LL+IM	0.67	1.16	ksi			LL+IM	-1.18	-2.07	ksi
		Σ	3.13	4.28	ksi			Σ	3.53	5.07	ksi

AISC/NSBA Design Example 4 – Negative Bending

2. Negative bending checks
   - 2.1 Compute composite section properties
   - 2.2 Extract bending moments and lateral bending stresses from the FEA model
   - 2.3 Compute principal bending stresses
   - 2.4 Verify the strength design equations

Strength check, tension flange (Eq. 6.10.8.1.3-1)

	f_{bu}	45.70	ksi
	F_{yf}	50	ksi
Art. 6.5.4.2	ϕ_f	1.0	
	$\phi_f R_h F_{yf}$	50	ksi
Eq. 6.10.8.1.3-1	$f_{bu} \leq \phi_f R_h F_{yf}$	0.91	OK

Strength check, compression flange (Eq. 6.10.8.1.1-1)

	f_{bu}	42.61	ksi
	f_{l1}	5.07	ksi
Eq. 6.10.1.10.2-1 & Eq. 6.10.1.10.2-3	R_b	1.0	
Eq. 6.10.8.2.3b-3	r_t	7.41	in
Eq. 6.10.8.2.3a-4	L_p	16.37	ft
Unbraced length	L_b	20.50	ft
	C_b	1.00	
Eq. 6.10.1.6-2	$L_b \leq 1.1L_p\surd(C_bR_b/(f_{bu}/F_{yc}))$	NO	
Eq. 6.10.8.2.3b-2	F_e	260.0	ksi
Eq. 6.10.1.6-4	f_l	5.16	ksi
	AF	1.017	
Eq. 6.10.8.2.2-3	λ_f	4.50	
Eq. 6.10.8.2.2-4	λ_{pf}	9.15	
Art. 6.10.8.2.2	F_{yr}	35.0	ksi
Eq. 6.10.8.2.2-5	λ_{rf}	16.12	
Art. 6.10.8.2.2	$F_{nc,FLB}$	50.00	ksi
Eq. 6.10.8.2.3a-5	L_r	55.9	ft
Art. 6.10.8.2.3a	$F_{nc,LTB}$	48.43	ksi
	$f_{bu} + 1/3f_l$	44.33	ksi
Eq. 6.10.8.1.1-1, FLB	$f_{bu} + 1/3f_l \leq \phi_f F_{nc}$	0.887	OK
Eq. 6.10.8.1.1-1, LTB	$f_{bu} + 1/3f_l \leq \phi_f F_{nc}$	0.915	OK

AISC/NSBA Design Example 4 – Shear

3. Shear check
    - 3.1 Extract the shear forces from the FEA models
    - 3.2 Calculate the shear resistance and verify the strength design equation

Applied shear

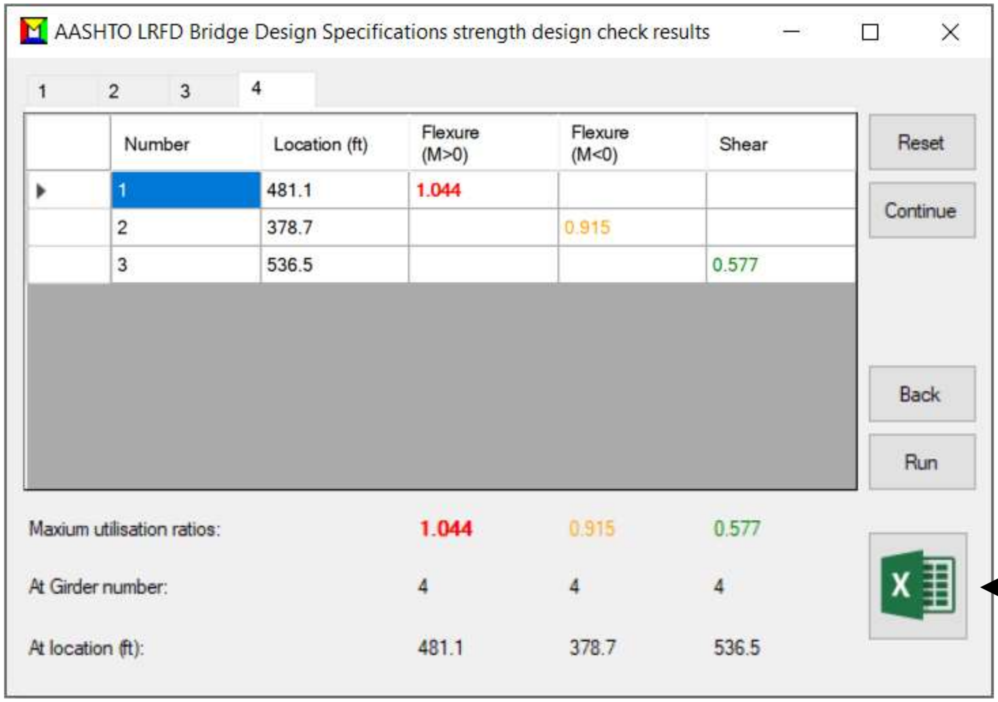
$V_{DC1\text{-}S}$	-22.8	kips
$V_{DC1\text{-}C}$	-87.1	kips
V_{DC2}	-20.1	kips
V_{DW}	-19.2	kips
V_{LL+IM}	-75.1	kips
V_u	322.8	kips

Shear resistance (Eq. 6.10.9.1-1)

	F_{yw}	50	ksi
	E	29000	ksi
	D	84	in
	t_w	0.5625	in
	D/t_w	149.3	
Transverse stiffener spacing	d_0	84	in
	Interior or end panel?	END	
Eq. 6.10.9.3.2-7	k	10.0	
Art. 6.10.9.3.2	C	0.408	
Eq. 6.10.9.3.3-2	V_p	1370.3	kips
Eq. 6.10.9.3.3-1	V_n	559.5	kips
Art. 6.5.4.2	ϕ_v	1.0	
	$\phi_v V_n$	559.5	kips
Eq. 6.10.9.1-1, end panels	$V_u \le \phi_v V_n$	0.58	OK
	b_{fc}	21	in
	t_{fc}	1	in
	b_{ft}	20	in
	t_{ft}	1	in
Eq. 6.10.9.3.2-1	$2Dt_w/(b_{fc}t_{fc}+b_{ft}t_{ft}) \le 2.5$	YES	
Eq. 6.10.9.3.2-3	V_p	1370.25	kips
Eq. 6.10.9.3.2-2	V_n	1058.3	kips
	$\phi_v V_n$	1058.3	kips
Eq. 6.10.9.1-1, interior panels	$V_u \le \phi_v V_n$	0.31	OK

AISC/NSBA Design Example 4 – Summary

A summary of the design checks is provided in the software, together with an Excel button to open the corresponding design checks.



	Number	Location (ft)	Flexure (M>0)	Flexure (M<0)	Shear
▶	1	481.1	1.044		
	2	378.7		0.915	
	3	536.5			0.577

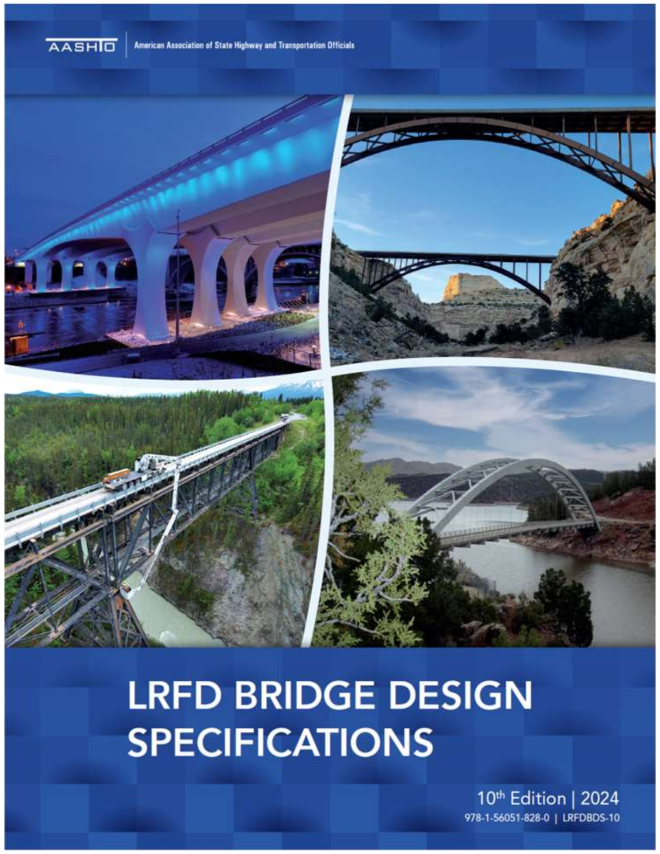
Maxium utilisation ratios:	1.044	0.915	0.577
At Girder number:	4	4	4
At location (ft):	481.1	378.7	536.5

Button to open the Excel spreadsheets showing the strength design checks at all design locations

Concluding Remarks

1. The latest software release (v4.0) now implements the bending and shear strength design checks in compliance with the latest edition of the AASHTO LRFD Bridge Design Specifications (10th Edition, 2024).
2. As mBrace3D implements refined 3D shell models, this means optimal accuracy compared to more traditional beam or grid models.
3. Design equations are verified by extracting the results from different load cases: DC1-S, DC1-C, DC2, DW , and LL+IM.
4. Steel grades as well additional transverse web stiffeners and longitudinal deck reinforcement are defined prior to running the design checks.
5. 2nd order lateral bending stresses are evaluated using the AASHTO 6.10.1.4 Equation, where the unbraced length at the design location is calculated automatically based on the cross-frame arrangement specified by the user.
6. Additional parameters, such as the hybrid factor, web load-shedding factor, and shear panel type are also evaluated automatically.
7. The method implemented is the opposite of a black box approach, as all the calculations can be verified in Excel if necessary. These calculations may also be used in calculation reports for design documentation.

Reference



American Association of State Highway and Transportation Officials (2024). "LRFD Bridge Design Specifications (10th ed.)". Washington, D.C.